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LARGE WOOD RETENTION IN RIVER CHANNELS: THE CASE OF THE FIUME TAGLIAMENTO, ITALY

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ABSTRACT

After more than 300 years of widespread and intensive river management, few examples of complex, unmanaged river systems remain within Europe. An exception is the Fiume Tagliamento, Italy, which retains a riparian woodland margin and unconfined river channel system throughout almost the entire 170 km length of its river corridor. A research programme is underway focusing on a range of related aspects of the hydrology, fluvial geomorphology and ecology of the Tagliamento. This paper contributes to that programme by focusing on large wood retention. The paper adopts a simple force:resistance approach at the scale of the entire river corridor in order to identify reaches of the river with a high wood retention potential. Information on the character of the river corridor is derived from 1:10 000 scale topographic maps. A range of indices measured at 330 transects across the river corridor supports a classification of the geomorphological style of the river which reflects the presence and abundance of properties previously identified in the literature as large wood retention sites. This classification provides a qualitative representation of the 'resistance' of the corridor to wood movement and thus its overall wood-retention potential. The map-derived indices are also used to extrapolate estimates of the ten year return period flood to each of the 330 transects so that the downstream pattern of unit stream power can be quantified as an index representing 'force' in the analysis. Although input of wood is an important factor in many river systems, it is assumed not to be a limiting factor along the Tagliamento, where riparian woodland is abundant.

Field observations of large wood storage illustrate that wood retention at eight sites along the river reflects the presence and abundance of the features incorporated in the classification of geomorphological style, including the complexity of the channel network, the availability of exposed gravel areas, and the presence of islands. In general at the time of survey in August 1998, open gravel areas were estimated to store approximately 1 t ha^{-1} of wood in single-thread reaches and 6 t ha^{-1} in multiple-thread reaches. Established islands were estimated to store an average of 80 t ha^{-1} of wood. Nevertheless, there was considerable variability between sites, and pioneer islands, which are not represented on maps or readily identified from air photographs because of their small size, were estimated to store an order of magnitude more wood than established islands. Furthermore, the wood storage from this sample of eight sites did not reflect variability in estimated unit stream power.

A series of areas for further research are identified, which can be explored using field data, and which will throw more light on the processes of wood retention in this extremely dynamic fluvial environment. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS: large woody debris; unit stream power; river islands; river planform

INTRODUCTION

Rivers of western Europe lost riparian floodplain forests and experienced early forms of channelization, involving the loss of secondary channels for the purposes of navigation and also for floating timber, prior to the 16th century. This was followed by the more far-reaching impacts of the land-drainage, channelization and regulation schemes of the 18th, 19th and 20th centuries. Early documentary and cartographic evidence shows that before the era of human impacts, river systems drained corridors containing longitudinally extensive riparian woodlands and had morphologically complex channels including sectors with two and

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sometimes multiple channels and vegetated islands (Large and Petts,1996; Petts, 1990; Petts *et al.*, 1989). Large wood pieces would have provided a key influence on the geomorphology and ecology of these river systems (Maser and Sedell, 1994; Sedell and Froggatt, 1984).

After more than 300 years of widespread and intensive, river management, few examples of complex, unmanaged, river systems remain within Europe. An exception is the Fiume Tagliamento, Italy (Müller, 1995). The catchment, particularly in the downstream areas, is subject to some agricultural and industrial development but the river retains a riparian woodland margin throughout almost its entire 170 km length. Indeed, evidence from air photographs taken between 1944 and 1946 suggests a dramatic increase in riparian woodland cover over the last 50 years, which may reflect the abandonment of riparian margins by farmers who prefer to work larger fields that are better adapted to mechanized agriculture (Thévenet *et al.*, 1998). The most downstream 15 km has been channelized and closely confined between flood embankments, but the remainder of the river's length is essentially morphologically intact. Furthermore, although there are hydrological changes as a result of some water abstractions for hydro-power, irrigation and public water supply within the catchment, these are not sufficient to significantly affect the large, channel-forming discharges which exceed the magnitude of the natural mean annual flood. As a result, it is possible to use observations from the Tagliamento to investigate interactions between hydrology, geomorphology and ecology along a large European river in a relatively natural setting. A research programme is underway focusing on a range of aspects of the hydrology, geomorphology and ecology of the Fiume Tagliamento (Ward *et al.*, 1999, in press). This paper reports on the first stages of an evaluation of the role of large woody debris in influencing the geomorphology and ecology of the river.

This paper adopts a simple force:resistance approach to appraise interactions between hydrology, geomorphology and vegetation in order to identify reaches of the Tagliamento with a high wood retention potential. Information from 1:10 000 scale maps is used to estimate downstream patterns in the availability of locations where large wood can be retained (resistance) and in the unit stream power (force) available to move wood downstream. Field-based estimates of exposed large wood storage within eight reaches of the river are then used to evaluate the degree to which observed large wood storage reflects the estimated interaction of force and resistance.

Although large wood supply is also an important control on wood transport and retention, in this analysis it is assumed not to be a limiting factor because of the longitudinally extensive ribbons of riparian woodland bordering the active zone of the river. In the field, this woodland exhibits a patchy age structure, which is indicative of frequent disturbance and subsequent recolonization and which indicates the role of the woodland as a major source of wood debris. Commonly occurring tree species include *Alnus incana, Populus nigra*, and five species of willow (*Salix alba, S. daphnoides, S. elaeagnos, S. purpurea, S. triandra*). All of these species are capable of rapid colonization and growth on exposed riparian areas (Edwards *et al.*, in press). Furthermore, analysis of air photographs of a 125 ha section of the active zone at three dates (1984, 1986, 1991) has shown that the destruction and establishment of wooded islands has been extensive, although an approximately constant island cover has been maintained between 1984 and the present (Kollmann *et al.*, 1999). The destruction of islands provides an additional source of wood to the river. Moreover, interpretation of both the air photographs and field evidence led Kollmann *et al.* (1999) to suggest that the succession from bare gravel to established wooded island takes about 10–20 years, which is further evidence of the rapid colonization and establishment of the riparian tree species.

THE FIUME TAGLIAMENTO

The Fiume Tagliamento (Figure 1) is a gravel-bed river located in northeastern Italy. More than 70 per cent, of its catchment area is located within the southern fringe of the Alps. The river rises at 1195 m a.s.l. and the highest peak in the catchment is Mt Coglians (2781 m). For the first 30 km of its course, the river flows in an easterly direction through alternating steep gorges (slope 0·1–0·04) and more open basins (slope 0·02–0·01). It then drains a widening valley, flowing a further 30 km eastwards and then *c*. 25 km southwestwards, with a gradually declining slope (0·01–0·005). Within this central section of the river's length, it receives flow and sediment inputs from several large tributaries including the Degano, But and Fella. This central section is

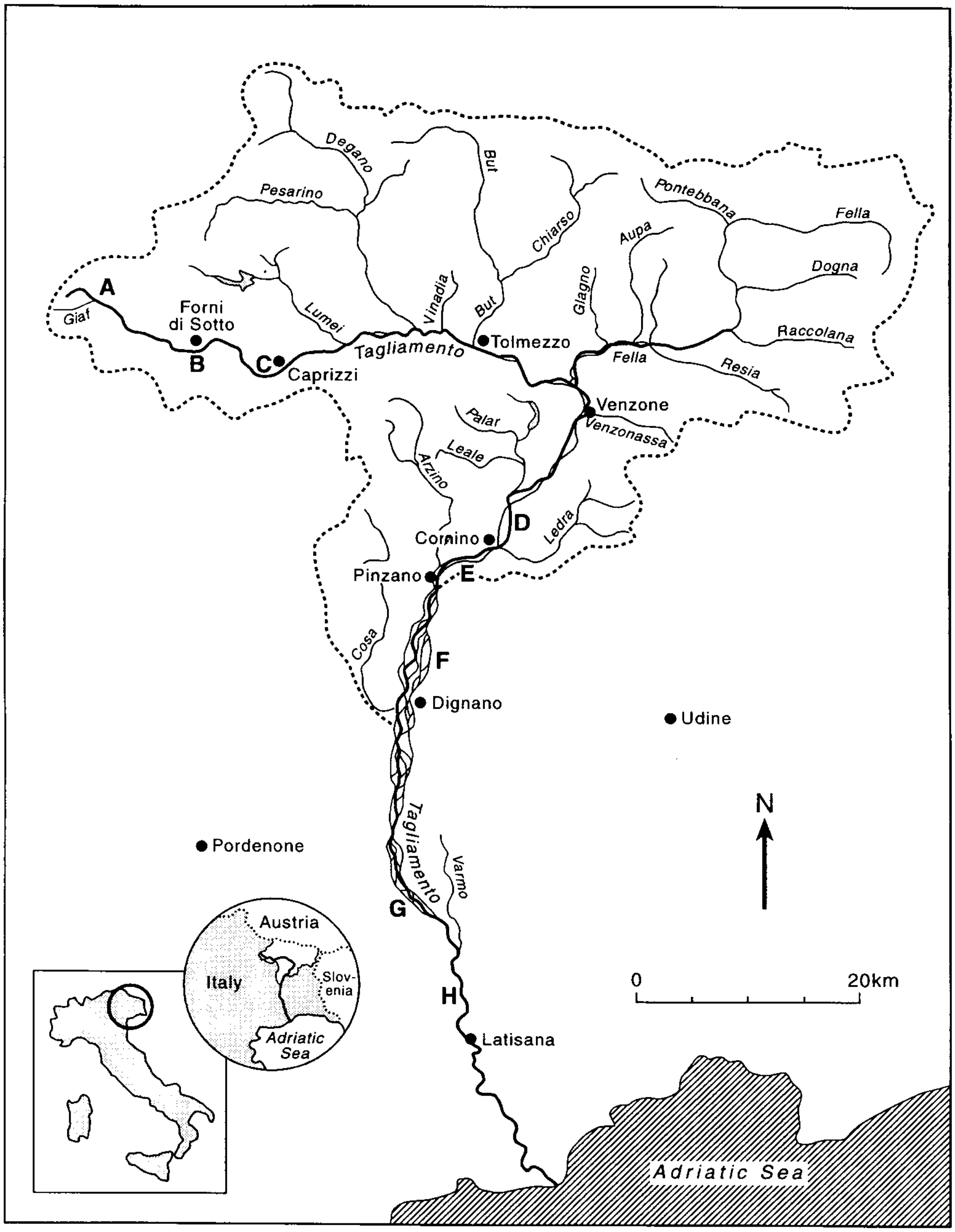

Figure 1. The catchment of the Fiume Tagliamento

terminated by a narrow bedrock-confined constriction at Pinzano. Thereafter, the river drains across a wide plain to the Adriatic sea.

CONTROLS ON THE RETENTION OF LARGE WOOD IN RIVER SYSTEMS

Within a river system, the controls on the retention of large wood fall into four categories: forest character (tree sizes, species and density); hydrological processes (both river discharge and sediment transport

regimes); geomorphology (river corridor width, slope and form; river channel bank and bed sediment calibre; river channel size, pattern and dynamics); and management as it affects the above three groups of factors.

In less-managed systems, where river channels are morphologically intact and are bordered by riparian forest throughout their length, the relative importance of forest character, hydrological processes and geomorphology changes in a downstream direction (Gurnell *et al.*, 1995).

In very small headwater streams, the character of the forest is of over-riding importance. Many wood pieces are large enough to span the channel width, even being supported above the channel by the valley sides in very narrow river corridors. Once they have fallen into the river channel, large wood pieces are relatively immobile because stream discharges are not sufficiently powerful to move them. The result is an apparently random distribution of wood pieces within and across the channel, governed largely by the locations of wood input and the rate of wood decay. Thus, input mechanisms such as local tree fall from bank undercutting and blow down, and, in very steep terrain, hillslope processes such as mass failures and debris torrents (Keller and Swanson, 1979), dictate the distribution of large wood within the stream system.

As streams increase in size, large wood pieces are less likely to be long enough to span or jam across the channel and are more readily mobilized by the increasingly powerful stream discharges. As a result, other controls begin to have a significant influence on large wood retention. Whilst stream discharges may not be able to move the largest pieces of wood, intermediate-sized pieces can only be retained if structures are available to brace them against the flow. Such retention structures include the very largest wood pieces, riparian vegetation (particularly the trunks and exposed roots of riparian trees), other large roughness elements within the channel such as boulders, and morphological constrictions and planform irregularities of the river channel. The result is the development of accumulations or dams of wood which are braced by a few larger pieces of wood, but which then build by trapping mobile wood pieces of all sizes. This produces a trend whereby the average size of wood pieces retained and the spacing between accumulations increases with the size/width of the stream (Bilby and Ward, 1989). The dominant control category here is the hydrological regime, since this drives the periodic movement of wood pieces during high flows and controls the size of wood pieces that move.

Once the river channel becomes so wide that it is no longer possible for large wood to span the channel, and the discharge is sufficient to transport most of the wood, regardless of size, during high flows, then river geomorphology becomes the most important control on wood retention. In particular, the geomorphological style of river channel (meandering, braided, island braided etc.) dictates the availability of locations for large wood retention (Piégay and Gurnell, 1997).

Thus in unmanaged small streams, wood is distributed in a near-random pattern reflecting where it enters the channel. With increasing stream size, debris dams become the characteristic form of debris accumulation. Smaller debris washed out of the channel during floods may form accumulations around the upstream sides of individual trees and ribbon-like trash lines close to the channel margin. In larger river systems, the morphology of the river channel controls the locations of large wood retention. Sites that have been observed to retain wood within large rivers include:

(i) side streams/distributary channels that are sufficiently narrow to retain debris dams similar to those found on small streams (Piégay, 1993);
(ii) floodplain woodland which can trap debris as lateral ribbons parallel to the channel margin or as patches of debris around individual trees (Piégay and Gurnell, 1997);
(iii) vegetated islands, which can brace large wood against upstream margins or can accumulate wood in sheltered areas along the sides and in the lee of islands (Hickin, 1984); and
(iv) in-channel features within the active zone of the channel where wood can be braced, resulting in the accumulation of wood as jams at the apex of bars (Abbe and Montgomery, 1996) and on the outer margins of meanders bends (Piégay and Marston, 1998); as a component of the organic material deposited within concave-bank benches (Hickin, 1984); and as strand lines or in more randomly distributed debris accumulations and individual wood pieces along channel margins and bar surfaces (e.g. Malanson and Butler, 1990).

Management moderates the role of the above groups of factors and so has important effects on the distribution and character of wood within river systems. Riparian woodland management changes the species composition and age structure of trees from which large woody debris is generated. In particular, tree thinning and felling can lead to the introduction of many small pieces of wood, which are readily moved by the river. In addition the harvesting of trees reduces the input of the very largest pieces of wood which would normally form the key pieces in debris accumulations. Hydrological management involves changes in the river flow regime, which changes the frequency and transport distance of wood pieces of different sizes. Channel management, which often involves techniques to increase the flow conveyance of river channels, reduces channel wood retention capacity and actively removes wood from the river channel. In general, the impact of management is to reduce the size of wood pieces delivered to and stored within the channel system and to reduce the wood retention capacity of the channel so that the mobility of wood increases.

With respect to the Fiume Tagliamento, it can be hypothesized that within this relatively unmanaged river system, large wood supply is not a limiting factor. Thus, the retention of large wood results from the interaction of the resistance of the river to the movement of large wood and the force available to move the wood. The river's resistance depends on the availability of particular morphological features, which have been observed to trap large wood. These can be summarized through a classification of the geomorphological style of the river (Piégay and Gurnell, 1997). Unit stream power provides an index of the power available to transport the wood per unit width of channel. The following two sections estimate downstream patterns of resistance and power along the Tagliamento.

RIVER GEOMORPHOLOGICAL STYLE AS AN INDEX OF RESISTANCE TO LARGE WOOD MOVEMENT

Data sources

A classification of river geomorphological style along the Tagliamento was based upon the distribution of features known to trap large wood. The analysis was based upon information derived from 1:10 000 scale maps produced by the Regione Autonoma Friuli-Venezia Giulia, Italy. These maps are based on surveys undertaken between 1986 and 1990. The aim was to provide an objective classification of geomorphological style of the river that could be used as a qualitative tool for assessing variations in the potential for large wood retention within different reaches.

Although features within the active zone of the river, such as channels, bars and islands, are extremely dynamic, the analysis of air photographs and field data by Kollmann *et al.* (1999) suggests that no major changes in the total area of islands has occurred in their study reach since 1984. Furthermore, although there has been an expansion in the area under riparian woodland and islands over the last 50 years, air photographs taken in 1944–46 indicate that the longitudinal structure of the active zone of the river has not undergone any significant changes. Therefore, 1:10 000 scale maps representing the river in 1986–90 were selected as a geographically correct, single-scale information source from which measures of a variety of indices could be drawn in a consistent way to derive a qualitative geomorphological classification.

Many problems are encountered in attempting to identify geomorphological features along river corridors from maps and remotely sensed sources such as air photographs. For example, it is difficult to identify the presence of small features and the subtle variations in the topographic expression of many features. A specific problem associated with maps is the generalization or omission of some features. Furthermore, the representation of dynamic features such as the complex, multi-thread, water-filled channels of the Tagliamento, is strongly influenced by the time of mapping or photography.

To ensure consistency within the derived data, precise protocols were defined for extracting geomorphological indices from the 1:10 000 scale maps. The indices may not be ideal from a geomorphological perspective but the protocols were designed to generate robust and repeatable observations. Subsequent field work will refine interpretation of the indices and the associated classification of geomorphological style. Figure 2 illustrates some of the features and indices referred to below.

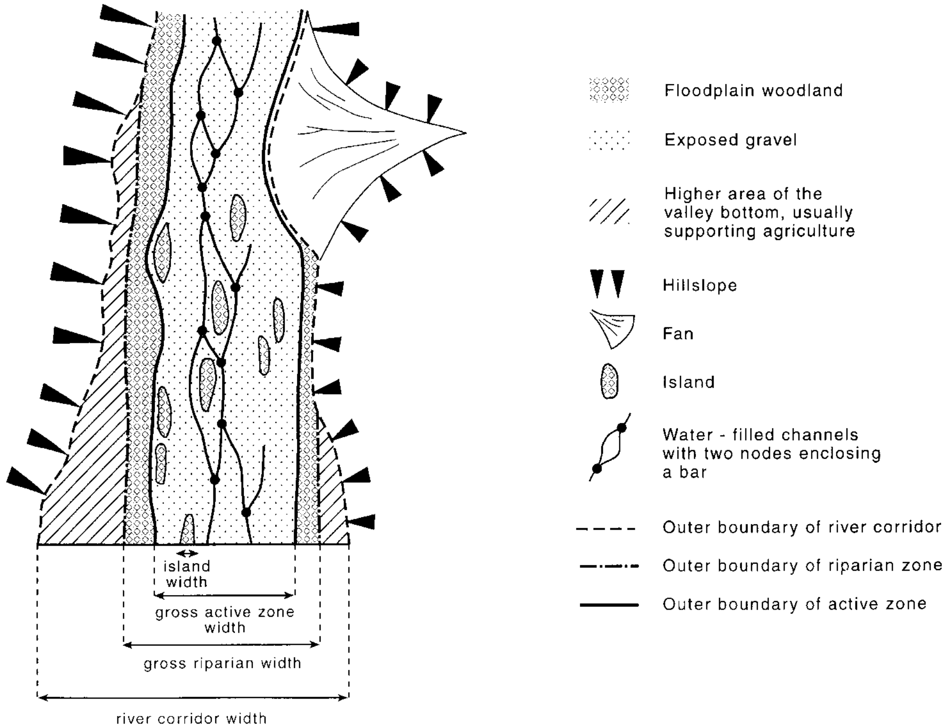

Figure 2. Mapped features used to develop a classification of river geomorphological style

Derivation of map-based indices

A total of 330 transects were drawn onto the 1:10 000 scale base maps at 500 m intervals along the main channel of the Tagliamento from the source to the mouth of the river. For each of these transects, three types of data were collected.

(i) Linear measures and counts across the river corridor transects

- *Island width*: the total width of islands intersected by the transect. Here an island is defined as a discrete area of vegetation completely surrounded by either water-filled channel or exposed gravel (Ward *et al.*, in press).
- *Gross active zone width*: the width of the currently active zone of the river, including water-filled channels, areas of bare sediment (mainly gravel) and islands.
- *Gross riparian width*: the width of the currently active zone of the river plus adjacent areas of riparian woodland. The marginal band of riparian woodland is interpreted to be a wooded mosaic, which is essentially ephemeral, being periodically reworked as a result of lateral displacement of the active zone (Bravard and Gilvear, 1993). Field observations have confirmed that these areas of riparian woodland usually correspond with the contemporary floodplain.
- *River corridor width* (to a maximum of 2 km): the width of the topographically low area on either side of the river. It extends as far as the adjacent hillslopes, fans or any other major topographic features that confine the river system. It includes the currently active zone, marginal bands of riparian woodland and zones under other land use, primarily agriculture, which are interpreted to be higher, more stable, terrace areas of the corridor.

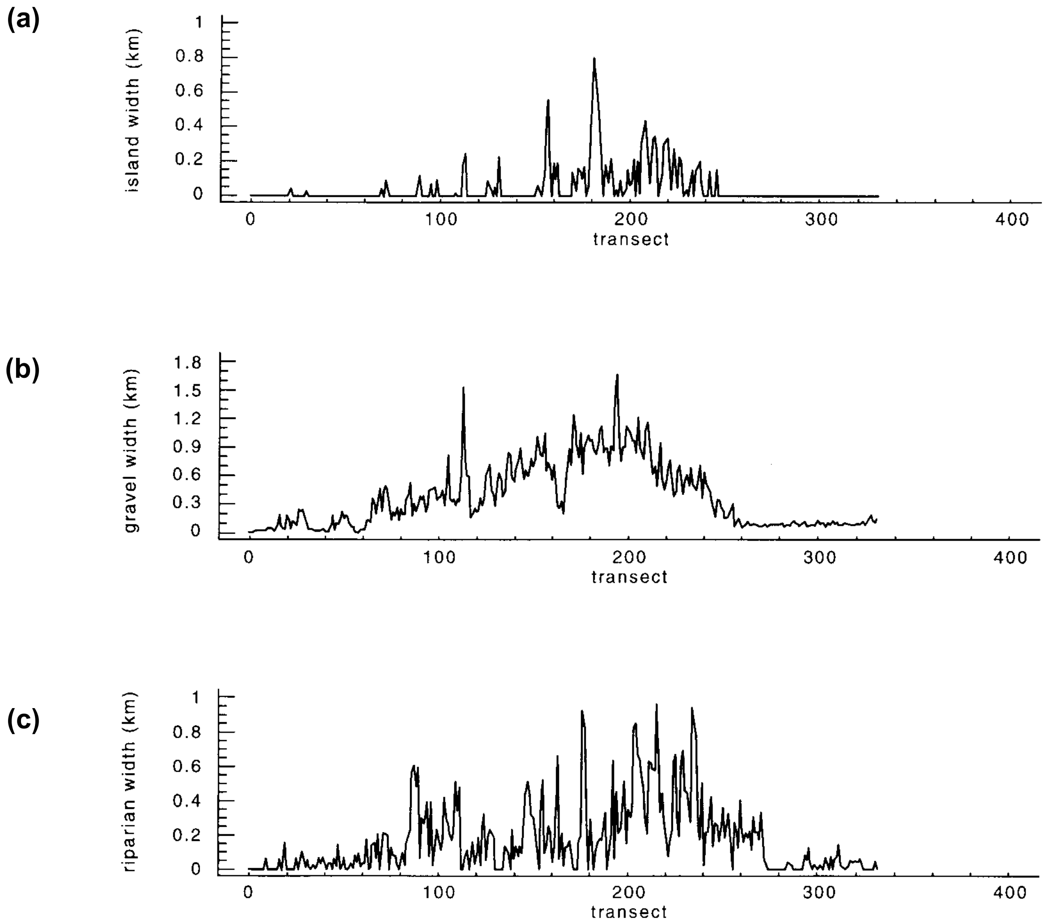

Figure 3. Island width (a), gravel width (b) and riparian width (c) measured at each transect from transect 1 (upstream) to 330 (downstream)

- From the above measures, the *width of the riparian zone* (i.e. gross riparian width minus gross active zone width), and the *width of exposed gravel* (including water-filled channels) within the active zone (i.e. gross active zone width minus island width) were calculated.
- The *number of water-filled channels* at the time of map survey, *the number of vegetated islands* and *the number of major bars* (areas of gravel surrounded by water-filled channels) intersected by the transect were counted.
- The *altitude* of the lowest spot height in or near the transect.

(ii) Areal measures and counts of features within 500 m reaches between pairs of transects

- The *number of islands, major bars and nodes within the channel network.*
- The *maximum, minimum and mean length of islands and major bars.*
- The *area of exposed gravel* (including water-filled channels) between transects, estimated as the product of gravel width at the transect and the inter-transect distance of 500 m.
- The total *area of islands* between transects. This is estimated by assuming that the observed islands are each lozenge-shaped with the observed mean length and width governed by an apex angle of 50° (Rachocki, 1981).

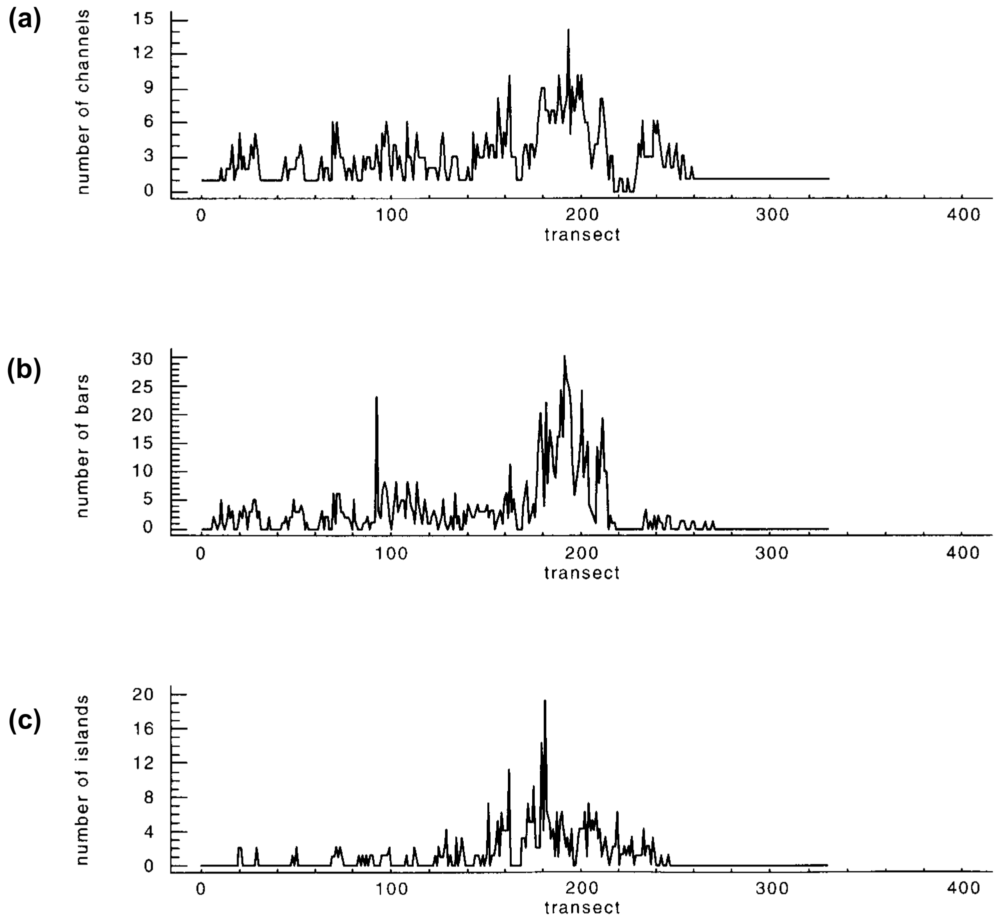

Figure 4. Number of channels (a), number of bars (b) and number of islands (c) measured at/between transects from transect 1 (upstream) to 330 (downstream)

- *Bed slope* estimated from the lowest spot heights at the upstream and downstream transects.

(iii) Measures relating to the upstream catchment

- *Distance from source.*
- *Catchment area.*

Downstream patterns in the indices

Clear downstream patterns were evident in all of the indices. For example Figure 3 illustrates how the width of exposed gravel, islands and riparian zone rise to their maximum values within the zone limited by transects 180–240 (i.e. river kilometres 90–120) and then decline downstream. Similar patterns are illustrated for the number of channels at each transect and bars and islands between transects (Figure 4), and for the number of nodes, and the area of exposed gravel and islands between transects (Figure 5). Although all these variables exhibit a similar downstream pattern, increasing from low values in the headwaters to reach

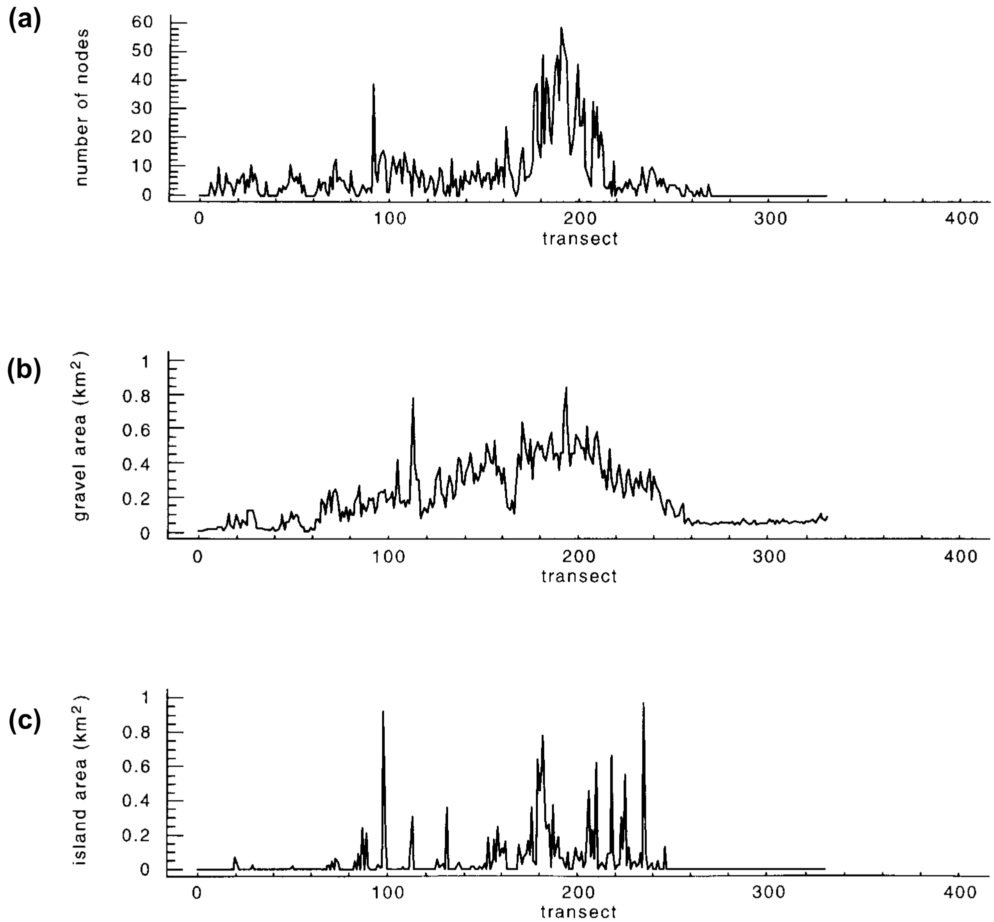

Figure 5. Number of channel nodes (a), gravel area (b) and island area (c) between transects from transect 1 (upstream) to 330 (downstream)

maximum values in the middle reaches and then declining in the downstream reaches (Figures 3 to 5), there are subtle differences in the downstream variations of the individual variables. In particular, the peaks in both the extent of vegetated islands and the width of the riparian zone are displaced downstream of the peak in the extent of exposed gravel. Moreover, there is remarkable variability in the number of water-filled channels. All of these spatial patterns are indicative of major changes in the character of the fluvial system along the length of the river.

A classification of geomorphological style

Information was available for each reach/transect for a large number of variables. A method of objectively classifying each 500 m reach according to the observed values of these measured variables was developed.

(i) The downstream *channelized section* of the river was separated from the remainder on the basis of its distinctive, smooth, single-thread planform bounded by artificial levees (Class 0).
(ii) *Division into single- and multiple-thread channels.* Where the number of channels was equal to 1, the reach was designated single channel. Where the number of channels was 0 or greater than 1, the reach

was designated as multiple thread. The rationale for designating the dry part of the river (number of channels = 0) as multiple thread was that, although there were no active channels during the relatively low flows at the time of mapping, other features of this dry section, particularly the large number of islands, suggest that it supports a multiple-thread pattern at intermediate flows. Field observations confirm the presence of multiple-thread flood channels in this dry section.

(iii) *Subdivision of single-thread reaches*. Single-thread reaches vary according to the degree that they support backwaters. Thus, they were divided into non-backwater (Class 1) and backwater (Class 2) reaches according to whether there were two or more channel nodes (junctions) within the reach.

(iv) *Subdivision of multiple-thread reaches*. Multiple-thread reaches were divided into four classes: Class 3: bar-braided (number of islands in the reach equal to zero); Class 4: bar-braided with occasional islands (island area/gravel area $< 0{\cdot}25$); Class 5: island-braided (island area/gravel area $> 0{\cdot}25$ and $< 0{\cdot}5$); Class 6: heavily island-braided (island area/gravel area $> 0{\cdot}5$).

(v) *Degree of lateral confinement* of the channel system was assessed by estimating the ratio of the width of the active zone to the width of the river corridor. The channel was deemed to be confined if the ratio was greater than 0·5.

The sequence of geomorphological style classes for each reach plotted in a downstream direction is shown in Figure 6. These 500 m reach classes were amalgamated into longer sections of channel of similar class. This classification of geomorphological style incorporates the key wood retention features described above and so gives an expression of the wood retention potential of the river system–the higher the class number, the greater the number and range of features that have been previously found to retain large wood.

STREAM POWER

The degree to which wood may be retained within river reaches is also influenced by the power of the river at channel-forming flows within each reach. Unit stream power has been shown to be an important control on sediment transport by rivers (e.g. Bagnold, 1966, 1980) and some parallels have been drawn between wood and coarse sediment transport (Braudrick *et al.*, 1997). The hydrological regime of the Tagliamento is extremely flashy. Snow melt and intense thunderstorms over the mountainous part of the catchment generate high flood flows, particularly in the spring and autumn. At Venzone (Figure 1, catchment area 1866 km^2) the average discharge is approximately 90 $m^3\ s^{-1}$, and the 2, 5 and 10 year floods are estimated to be 1100, 1600 and 2150 $m^3\ s^{-1}$ (Maione and Machne, 1982). Within the part of the catchment upstream of Venzone the average discharge has been shown to be related to catchment area raised to the power 0·955 (Mosetti, 1983). Downstream of Caprizzi (Figure 1), low flows are increasingly influenced by water abstractions, although these do not significantly affect the magnitude of channel-forming discharges (e.g. discharges in excess of the mean annual flood). Downstream from Venzone, the flows in the river are influenced by losses of water to an extensive alluvial aquifer, so that, for example, the mean annual flood only increases by 5 per cent between Venzone and Pinzano, whereas the catchment area increases by 22 per cent. Downstream from Pinzano the river flows over a major alluvial aquifer in its course to the Adriatic Sea. Modelling of 50+ year return period events by Maione and Machne (1982) suggests that there is a negligible change in the magnitude of flood peaks between Pinzano and Latisana (Figure 1).

Downstream patterns of total and unit stream power were estimated using the annual maximum flood series at Venzone (1885–1980) (Maione and Machne, 1982), the above observations on catchment hydrology, and estimates of catchment area to each of the 330 transects described above. Regional flood frequency analyses from many geographical areas (e.g. NERC, 1975; Thomas and Benson, 1970; SRAE, 1985) indicate that catchment area is the most reliable single catchment characteristic for estimating flood discharge magnitude. Thus, catchment area was used in the present study to extrapolate flood frequency estimates from Venzone to all 330 transects along the Tagliamento.

Before flood magnitude and total and unit stream power estimates could be extrapolated, a number of questions had to be considered. First, what is the appropriate return period flood to use in the analysis? The bankfull discharge is usually used to estimate the channel-forming stream power, where bankfull discharge

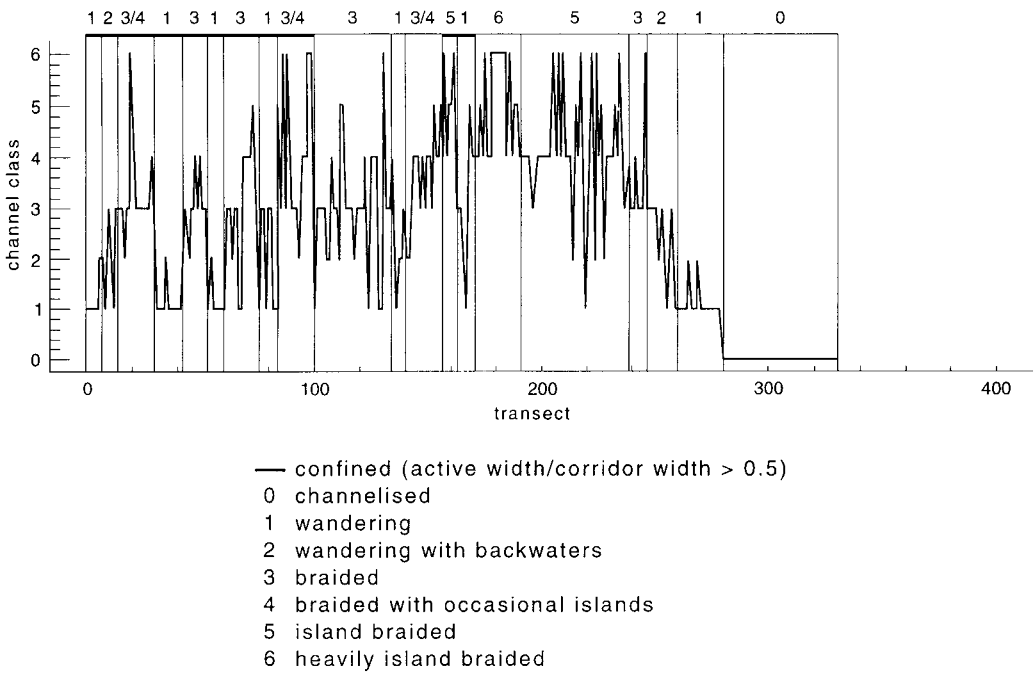

Figure 6. Classification of each transect according to geomorphological style and identification of groups of transects of similar style class

has been associated with 'a return period of between one and three years, with a model value of about 1·5 years' (Petts and Foster, 1985). However, Piégay *et al.* (in press) cite Wolman and Gerson (1978) in justifying their use of Q_{10} in an analysis of the River Drôme 'because of the greater effectiveness of less frequent floods in mediterranean ... climates'. The Tagliamento is subject to a mediterranean climate over much of its course, so Q_{10} was selected for the present study. Nevertheless, it is important to stress that the selection of the flood return period affects only the absolute, not the relative values of stream power along the river. Second, what is the appropriate regional flood frequency relationship to apply to the Tagliamento? The power indices to which regional flood discharge–catchment area relationships are raised vary between 0·8 and 0·95 depending upon the geographical area and the return period of the flood (e.g. Dunne and Leopold, 1978). Figure 7 illustrates the impact of raising catchment area to the powers 0·8, 0·9 and 1·0 on the transect estimates of Q_{10} extrapolated from Q_{10} observed at Venzone. There is little difference in the patterns displayed in the three graphs of Figure 7 and so 0·8 was selected as being the power recommended for application under similar environmental circumstances in French drainage basins (Piégay *et al.*, in press). Third, to what extent should factors other than catchment area be used to interpolate total stream power? Total stream power was estimated for each of the 330 transects as follows:

$$\text{Total Stream Power} = \rho g Q_{10} S$$

where ρ is fluid density = 1000 kg m^{-3}; g is gravitational acceleration (m s^{-2}); Q_{10} is the ten year return period flood peak discharge; S is the bed slope averaged over the upstream, downstream and current 500 m reaches to smooth extreme values generated by anomalous spot heights.

The hydrological information discussed above indicates that downstream of Venzone, the rate of growth of flood peak magnitude decreases rapidly even for large floods, and so the following procedure was used to gain the best estimate of downstream variations in total stream power, based upon discharge (Q_{10}) observations at Venzone and Pinzano. In the upper part of the catchment down to Venzone, total stream power was interpolated using catchment area raised to a power of 0·8 and the magnitude of Q_{10} at Venzone.

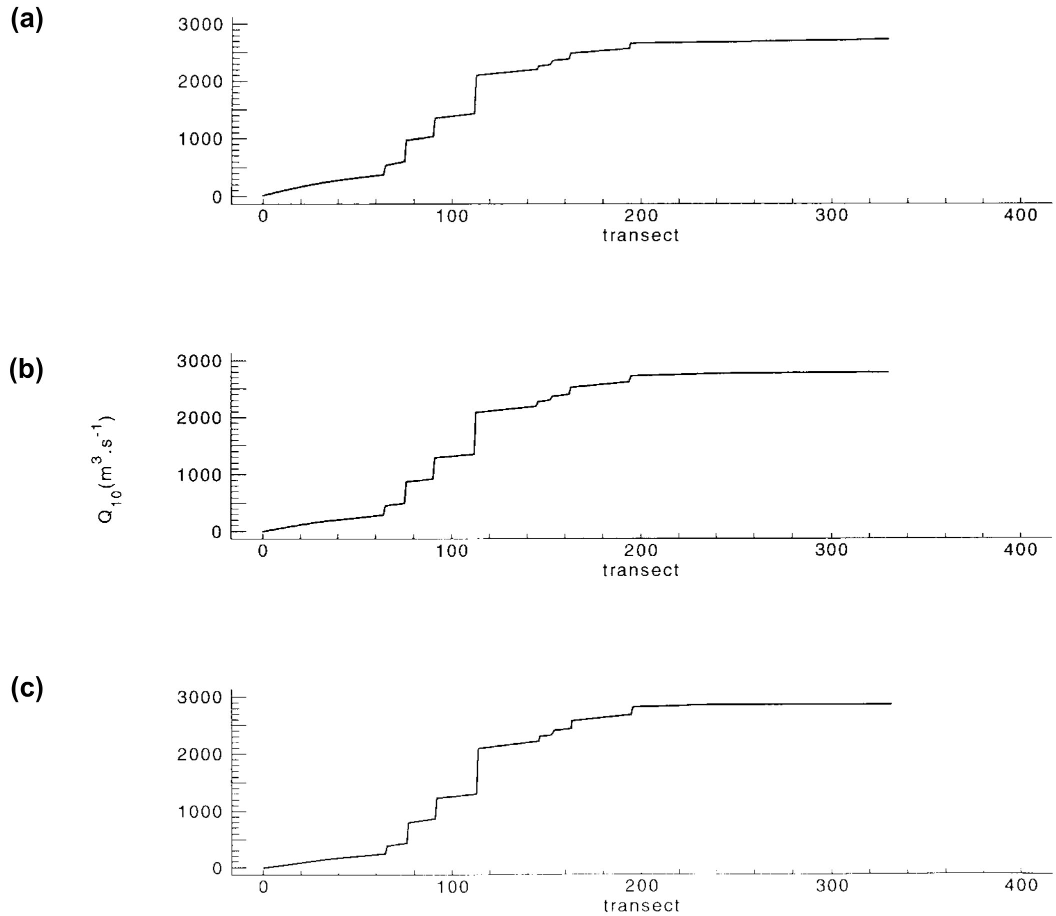

Figure 7. Estimates of the ten year return period flow for each transect based on flow records for the Venzone gauging station and catchment area raised to the power 0·8 (a), 0·9 (b) and 1·0 (c)

For transects between Venzone and Pinzano, the change in observed Q_{10} between the two gauging sites was distributed according to the increment in catchment area between transects. Downstream of Pinzano, Q_{10} was assumed to be the same at all transects. Figure 8a illustrates downstream changes in the estimate of total stream power using this approach. Since it is the part of the cross-section under bare gravel and water at low flow which will be primarily affected by the total stream power of flood events, unit stream power (Figure 8 b) was calculated by dividing the estimate of total stream power by the width of exposed gravel at each transect.

Figure 8 illustrates the downstream patterns in estimated total and unit stream power and the classification of river geomorphological style (Figure 8c). The part of the river affected by increasing total stream power is dominated by braided channel sections and steep single-thread gorge sections, whereas the major island-dominated reaches occur in the downstream zone of decreasing total stream power. Unit stream power does not vary greatly along much of the Tagliamento but there are some localized areas of high power which occur in six types of situation:

1. steep narrow headwater channels;
2. steep confined gorges;
3. rock-bounded channel constrictions;

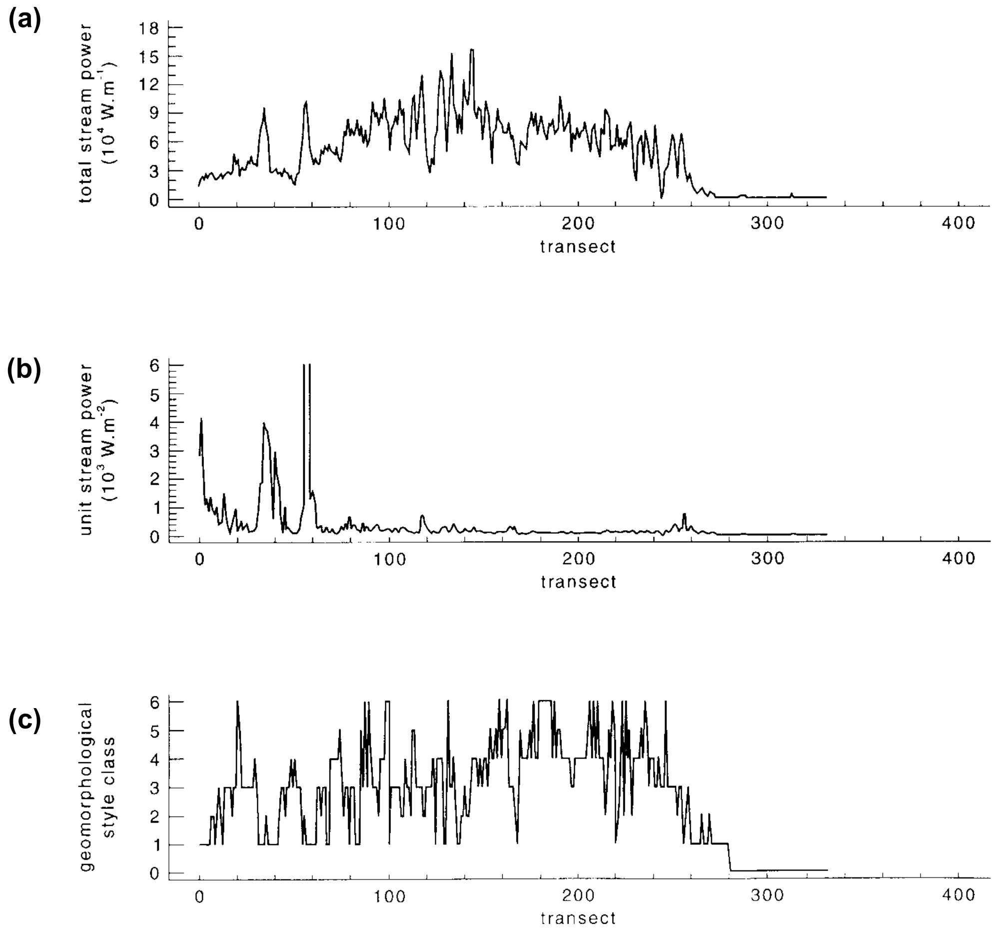

Figure 8. Estimates of (a) total stream power and (b) unit stream power. The maximum value, which extends above the upper limit of the graph, is *c.* 20 000 W m^{-2}, and occurs in a narrow, steep gorge section) in comparison with (c) geomorphological style class at the 330 transects

4. alluvial fan bounded constrictions;
5. immediately below major tributary junctions;
6. unconfined channel narrowing at the transition from multiple to single thread channel patterns.

In at least some of these locations, the increase in unit stream power may be sufficient to sweep many wood pieces through the affected channel sections in spite of the availability of retention sites.

FIELD OBSERVATIONS OF LARGE WOOD STORAGE

Observations of wood storage were gathered during August 1998 to test whether the map-based analysis of force and resistance separates locations of differing wood storage or loading. Surveys of the location and amount of stored wood were made close to eight of the 330 transects along the Tagliamento (Table I). Ideally, a larger number of survey locations would have been studied, but given the size of the river (gross active zone width up to 2 km), the eight reaches (A to H, Figure 1) represented the upper limit of what was realistically

Table I. Summary information on wood storage, geomorphological style class and unit stream power at eight locations along the Fiume Tagliamento

Strip	Nearest 500 m transect*	Class†	Strip length‡ (m)	Unit stream power§ (W m^{-2})	Active zone cover types (% surveyed area)			Estimated large wood storage (t ha^{-1})¶			
					Gravel + water	Pioneer islands	Established islands**	Total	Gravel + water	Pioneer islands	Established islands**
A	4	1	20	1270	94	0	6	2	1	–	24
B	27	3/4	140	170	83	0	17	29	21	–	57
C	51	3	160	80	93	0	7	9	6	444	25
D	149	3/4	730	120	100	< 1	0	6	4	787	–
E	162	5	730	140	94	2	4	27	7	911	148
F	186	6	890	70	69	< 1	31	21	7	293	44
G	241	3	620	150	91	< 1	9	24	7	334	186
H	254	2	240	230	95	5	0	89	1	1664	–

* The number of the transect immediately downstream of the surveyed strip. Transects are defined and numbered downstream from the source at 500 m intervals
† The generalized geomorphological style class for the length of river within which the strip is located (Figure 6)
‡ The length of the strip that was surveyed across the active zone
§ Unit stream power for Q_{10} (to the nearest 10 W m^{-2}) estimated at the nearest transect downstream of the surveyed strip
¶ A dash indicates that none of this cover type was present in the surveyed area
** The area of established islands refers to the vegetated area, whereas the wood storage estimate includes wood stored on gravel bars which form an integral part of the island

(a)

(b)

Figure 9. (a) Reach A and (b) reach B

achievable if high-quality surveys were to be undertaken. Figures 9–12 present photographs of sections of the Tagliamento within which the eight reaches are located. The surveyed strips were carefully selected to allow a detailed cross-sectional topographic survey in order that wood storage could be associated with particular topographic levels and geomorphological features. Because accurate topographic survey is difficult through dense woodland, some of the strips under-represented islands and so, where necessary, selected adjacent islands were studied and mapped separately with their topography being tied to the surveyed cross-profiles. At each site the location of every surface wood accumulation was mapped within a strip ranging from 50 to 100 m wide and extending across the entire active zone and into the riparian woodland margin. Surface wood accumulations were also mapped across the additional surveyed islands. Wood accumulations were classified into three types (shrubs and entire trees; jams; and individual logs or trunks) in a similar manner to Thévenet *et al.* (1998). Shrubs and entire trees were grouped together because most of the trees were alder, willow or poplar species, which have a similar complex structure to smaller shrubs with a large branch to trunk volume. In the case of logs, the length and diameter were measured so that their volume could be directly calculated.

(a)

(b)

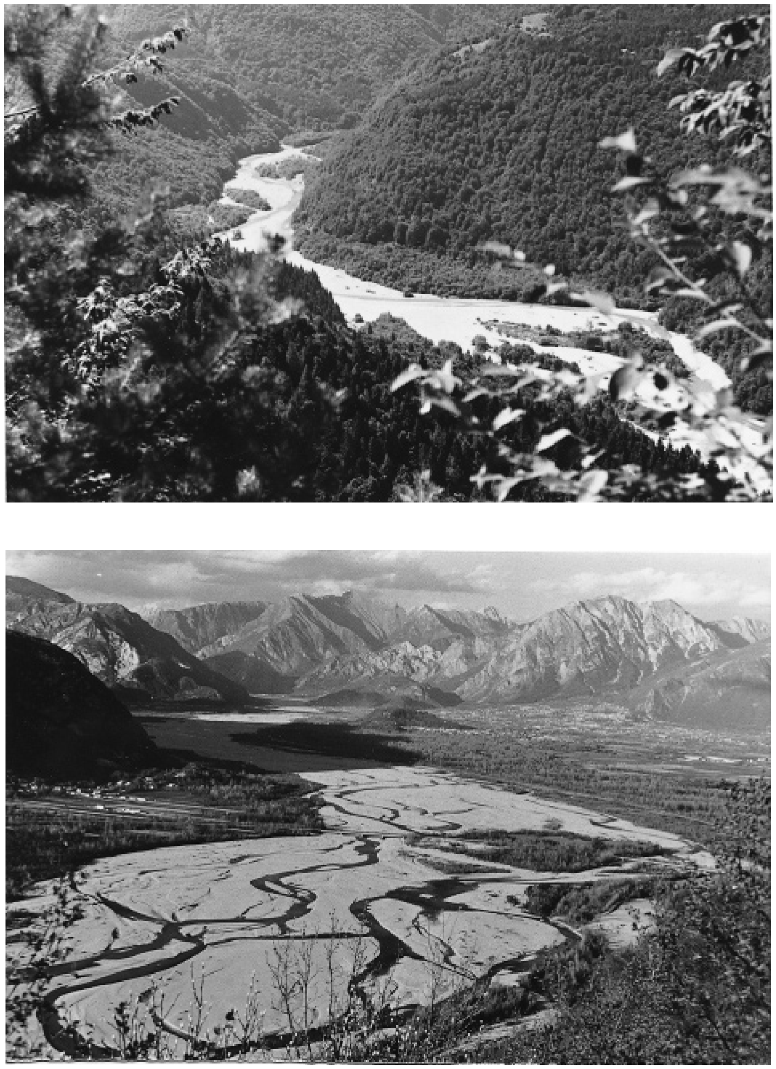

Figure 10. (a) Reach C and (b) reach D (located in the middle distance, upstream of the bridge)

For shrubs/trees and jams, the width, depth and height of the accumulations were measured so that the total wood/air volume of stored wood could be estimated for each of the eight surveyed strips. In addition to large wood exposed on gravel and established island surfaces, some wood accumulations had become partly buried in fine sediment and were sprouting to produce pioneer islands (Edwards *et al.*, in press). Pioneer islands can be seen in Figure 11 a, where the small dark patches towards the centre and right of the open gravel area in the photograph are mainly pioneer islands cored by single poplar trees. They can also be seen in Figure 12 b, where there are several pioneer islands cored mainly by jams of poplar with some willow in the foreground. The external dimensions of these partly buried shrubs/trees and jams, were measured in the same way as the exposed wood accumulations to provide a wood/air/sediment volume.

In order to obtain an estimate of the mass or loading of wood stored on the surface of each of the eight strips and additional islands, the total wood/air(/sediment) volume of shrubs/trees and jams and the total volume of logs were multiplied, respectively, by wood mass estimates of 50, 100 and 500 kg m^{-3}. Whilst the actual wood mass, particularly for the shrubs/trees, is highly variable, these mass estimates for the different wood/air(/sediment) volumes are based on those measured by Thévenet *et al.* (1998) for a large sample of wood

(a)

(b)

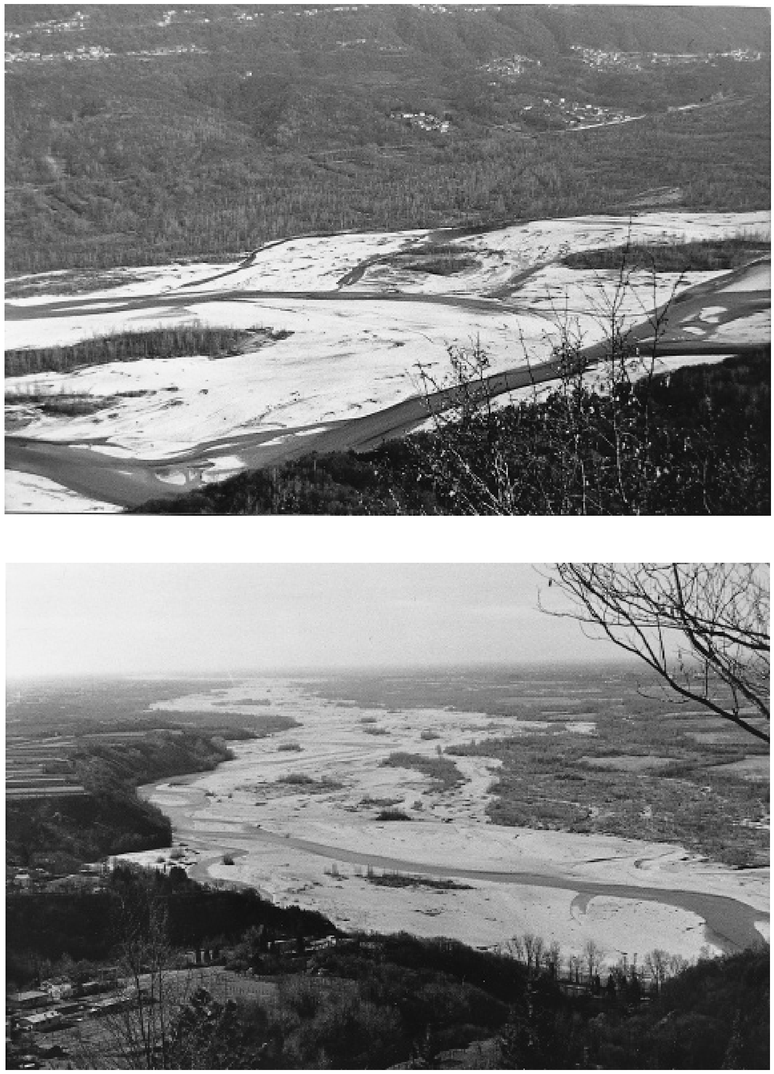

Figure 11. (a) Reach E and (b) reach F (located in the far distance)

accumulations along the rivers Ain and Drôme, France. These two French rivers have many morphological similarities to the Tagliamento and are bordered by many of the same riparian tree species. The detailed study by Thévenet *et al.* (1998) showed distinct differences in the wood/air densities of logs, jams and shrubs. Moreover, the wood/air densities of logs and jams were surprisingly consistent between accumulations and between rivers, whereas shrubs were more variable.

Further confidence in the transferability of these estimates was derived from the use of scaled photographs and field volumetric measurements from sites on the Tagliamento. These were used to assess the proportion of wood within the measured wood/air volumes of a sample of eight shrubs and eight jams. Photographs were taken from the side of each wood accumulation and from the direction of maximum solar illumination. In each case a grid was overlain on the photograph to cover the area delimited by the field-measured wood/air volume. Each grid intersection was inspected to assess whether or not it was underlain by illuminated wood, representing the surface wood layer. The proportion of intersections recorded as illuminated wood was taken to represent the proportion of wood in a slice through the largest cross-section of the accumulation. This

(a)

(b)

Figure 12. (a) Reach G and (b) reach H

estimate for the largest cross-section was translated into a wood proportion for the field measured wood/air volume by allowing for the approximately ellipsoid geometry of each accumulation within its overall length, width and height dimensions. A wood/air mass was then calculated by assuming a wood mass of 500 kg m^{-3}. The average (maximum and minimum) estimated values of mass for the sample accumulations were 122 (81, 220) and 62 (41, 110) kg m^{-3} for jams and shrubs, respectively. Given light penetration through the structure of the jam or shrub, this method of estimation is likely to slightly over-estimate the wood/air mass density value.

Table I summarizes the estimated exposed wood storage of each of the strip–island combinations in relation to the strip length, the percentage land cover types surveyed, the map-based estimate of unit stream power at the nearest transect downstream, and the generalized geomorphological style class for the length of river within which the strip was located (Figure 6). It is clear from the percentage cover of established islands surveyed that these are different from the expected cover based on the geomorphological style class. This is

partly a result of the method of site selection previously described, but also reflects the spatial and temporal variability of island cover in this dynamic system.

To provide a basis for relating wood storage to the retention features incorporated into the geomorphological classification, the total wood in each survey site is attributed to areas of exposed gravel (including river channels) and areas of pioneer and established islands. In the gravel category, debris accumulated along the edge of the gravel close to the gravel–riparian woodland margin was included, but wood stored within the riparian woodland was excluded. There are very significant differences in wood storage between the three surface types:

(i) with the exception of strip B, wood storage on exposed gravel surfaces is approximately 6 t ha^{-1} in multiple-thread (C, D, E, F, G) and 1 t ha^{-1} in single-thread (A, B) reaches;
(ii) established islands store variable amounts of wood, but storage is significantly higher than on open gravel areas;
(iii) pioneer islands are very limited in areal extent, but are very significant locations of wood storage.

The above observations clearly support the hypothesis that geomorphological class is an indicator of wood retention potential, since key features incorporated in the geomorphological classification store significantly different quantities of wood. In addition, pioneer islands, which are too small to be represented on 1:10 000 scale maps and which would be extremely difficult to identify on similar (i.e. 1:10 000) scale air photographs, may be very important influences on wood storage and on wood and island dynamics (Edwards *et al.*, in press)

Whilst the relationship between geomorphological style and wood retention is clear, it is more difficult to identify evidence from this sample of eight sites to support the hypothesis that stream power has a consistent influence on wood storage. No clear relationship can be identified from Table I between total or classified wood storage and stream power within the sample of eight reaches that were studied.

DISCUSSION AND CONCLUSIONS

A considerable amount of previous research has been devoted to the dynamics of wood debris in relatively small streams, where debris dams form the major type of wood accumulation. However, more research is required on larger river systems. This paper has hypothesized that along such systems, where the availability of a riparian woodland margin to supply wood is not a limiting factor, two major controls interact to determine the quantity and distribution of stored wood. The wood retention characteristics of the channel are reflected in its geomorphological style. The hydrological regime, as represented by unit stream power at channel-forming discharge, dictates the degree to which wood may be transported through the system.

An analysis of field observations suggests that as a first approximation the geomorphological style of the river influences the specific wood storage. Field surveys at eight sites located within sections of the river representative of all of the six identified geomorphological style classes illustrate that specific wood storage on open gravel increases in multiple-thread reaches and that it is particularly high where islands are present. However, field observations have illustrated the very high specific wood storage in pioneer islands, features which are not represented on maps and which are difficult to identify from other remotely sensed sources. The highest estimate of total specific wood storage was found in a single-thread reach with no established islands (strip H), which was expected on the basis of its geomorphological style and relatively high stream power to have very low wood retention. This high specific wood storage is almost entirely the result of the presence of pioneer islands.

The reported analyses coupled with field observations of river corridor characteristics raise a number of issues which require further study.

(i) The areal extent of islands varies between the strips sampled in the field and the map representation. Under-representation of islands in some of the field survey strips reflects the survey methodology that was adopted, but over-representation of islands cannot be explained in this way. Such differences may

reflect differences in island extent between the map (1986–90) and field (1998) survey dates. They also may reflect the size of features represented on the maps. Certainly, pioneer islands are not represented on maps and are not readily identified from remotely sensed sources. Size is an important property of island stability and structure as well as representing a filter in island identification on maps and from air photographs. It is necessary to establish a clear definition of an island in terms of its size, form and structure to provide a basis for a more informed analysis of island distribution, character and dynamics. In the field, it was clear that there were a range of different types of both established and pioneer islands, at and between the eight sites. In order to explore the storage of wood further, it is necessary to develop a typology of the islands that are present.

(ii) There is high variability in the quantity of wood stored by islands. In part, this is a function of the type of island. Whilst the separation of pioneer from established islands yields clear differences in specific wood storage, major differences remain within these classes. For example, note the differences in wood storage in pioneer islands in strips F and H, and on established islands in strips A and G. These differences result from contrasts in the type of wood stored and in the way in which the wood is stored.

(iii) There is a strong contrast in specific wood storage on the gravel areas of strip B in comparison with the other strips. This also reflects different modes of storage as well as differences in the type of wood stored.

(iv) The map analysis and the field data set do not support any simple relationship between unit stream power and wood storage. Field observations suggest that the association between unit stream power and wood storage is not direct but may be expressed through a more subtle joint interaction between power, stored wood and sediment availability and calibre.

(v) All of the information on large wood retention presented in this paper relates to wood which is stored on the land surface. No account is taken of buried wood, which from exposures along the eroded margins of established islands, may be extremely significant. Whereas buried wood may be of great ecological importance, the exposed wood has most significance in the hydrological and geomorphological interpretation of recent wood transport events. The quantity of exposed wood is particularly important in relation to the present force resistance analysis, where the pattern of wood retention is being interpreted through the force of a single hydrological event and the resistance offered by the contemporary surface forms of geomorphological features.

All of the above issues will be explored in subsequent papers by a more comprehensive analysis of the topographic, sedimentological, geomorphological and vegetational data collected at the eight field survey sites.

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